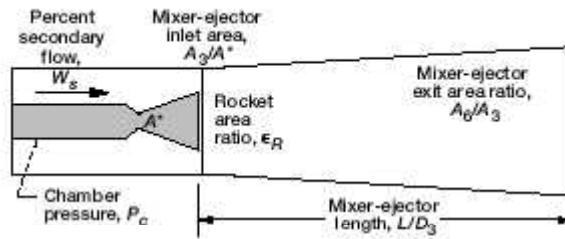


# Parametric Study Conducted of Rocket-Based, Combined-Cycle Nozzles

Having reached the end of the 20th century, our society is quite familiar with the many benefits of recycling and reusing the products of civilization. The high-technology world of aerospace vehicle design is no exception. Because of the many potential economic benefits of reusable launch vehicles, NASA is aggressively pursuing this technology on several fronts. One of the most promising technologies receiving renewed attention is Rocket-Based, Combined-Cycle (RBCC) propulsion. This propulsion method combines many of the efficiencies of high-performance jet aircraft with the power and high-altitude capability of rocket engines. The goal of the present work at the NASA Lewis Research Center is to further understand the complex fluid physics within RBCC engines that govern system performance. This work is being performed in support of NASA's Advanced Reusable Technologies program.

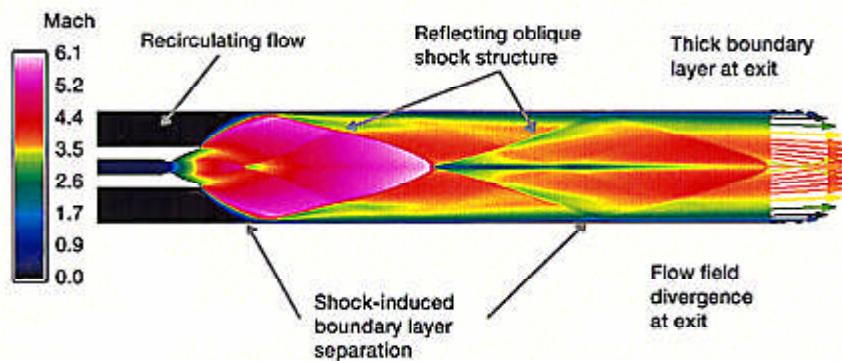
A robust RBCC engine design optimization demands further investigation of the subsystem performance of the engine's complex propulsion cycles. The RBCC propulsion system under consideration at Lewis is defined by four modes of operation in a single-stage-to-orbit configuration. In the first mode, the engine functions as a rocket-driven ejector. When the rocket engine is switched off, subsonic combustion (mode 2) is present in the ramjet mode. As the vehicle continues to accelerate, supersonic combustion (mode 3) occurs in the ramjet mode. Finally, as the edge of the atmosphere is approached and the engine inlet is closed off, the rocket is reignited and the final ascent to orbit is undertaken in an all-rocket mode (mode 4). The performance of this fourth and final mode is the subject of this present study. Performance is being monitored in terms of the amount of thrust generated from a given amount of propellant.



Description of RBCC nozzle geometry.

A statistical approach to experimental design was used to study the performance of the RBCC all-rocket mode. Six independent variables were considered at three values each: low, medium, and high (see the preceding schematic). The full design matrix of 729 cases was efficiently pared down to 36 cases by utilizing a D-optimal response surface design. This approach has enabled us to model the linear, curvilinear, and two-way interaction effects efficiently by running a minimum number of cases distributed throughout the six-dimensional design space. The details of this approach to experiment design are given in references 1 and 2.

The analysis of a given nozzle's performance was based on an involved computer simulation, commonly referred to as computational fluid dynamics (CFD). NPARC v. 3.0 software was used for these simulations to solve the axisymmetric, steady-state Navier-Stokes equations on multiblock meshes with the assumption of a perfect gas equation of state. For turbulent flow, closure was provided via the Spalart-Allmaras or Chien models. Simulations were executed on a variety of NASA computers, including Unix workstations and supercomputers. Specific impulse data were calculated by integrating the streamwise momentum flux and massflow across the exit plane of the RBCC nozzle. These values were then compared with the theoretical maximum that could be achieved by a thermodynamically similar isentropic engine. This comparison was reported as specific impulse efficiency. The results thus far have exhibited efficiencies as low as 78 percent and as high as 95 percent. The complex flow field evident in the following figure reveals some of the loss mechanisms involved in reducing thrust.



*RBCC nozzle flow field showing Mach number contours.*

The numerical simulations are complete, and the final analysis is underway. The results have revealed that several factors can have a significant effect on the mode-4 performance of RBCC systems. Overall length, mixer/ejector inlet area ratio, exit area ratio, primary rocket exit area ratio, and secondary flow are all capable of affecting the efficiency. More work is necessary to understand these effects for RBCC configurations outside of this particular design. Details of the computational fluid dynamics experiments and flow field analysis are included in reference 1. The details of the experimental design, statistical results, and implications for RBCC system design are discussed in reference 2. The results of this effort will be of use to other related efforts underway within NASA's Advanced Reusable Technologies program.

## References

1. Smith, T.D., et al.: Analysis of Rocket Based Combined Cycle Engine During Rocket Only Operation. AIAA Paper 98-1612, 1998.
2. Steffen, C.J., Jr., et al.: Rocket Based Combined-Cycle Nozzle Analysis Using NPARC. AIAA Paper 98-0954, 1998.

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